

# Tracing the origin of the single-spin asymmetries observed in inclusive hadron production processes at high energies

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## Abstract

It is pointed out that the existing models for the left-right asymmetries observed in single-spin inclusive hadron production processes can be differentiated experimentally. Several such experiments are proposed with which the basic assumptions of these models can be tested individually.

Striking left-right asymmetries ( $A_N$ ) for hadron production in single-spin high energy hadron-hadron collisions have been observed [1-9]. Significant effects have been seen [3-9] in the projectile fragmentation region in experiments with transversely polarized proton beams [3-9] as well as in those with transversely polarized anti-proton beams [5,9]. Data are now available not only for pions [3-6,9] but also for  $\eta$  meson [8], for kaons [9] and for  $\Lambda$  hyperon [7]. These results are of particular interest for the following reasons: First, such experiments are conceptually simple. Second, the observed effects were unexpected theoretically [10]. Third, until now, little information has been obtained on the *transverse* spin distributions in nucleon and the spin-dependent hadronic interactions in *transversely* polarized cases. Fourth, the observed asymmetries depend in particular on the flavor quantum numbers of the projectile and on those of the observed hadron [2-9]. Hence, they can also be used to study the flavor dependence of the spin distributions in the hadron.

A number of mechanisms [10-25] have been proposed recently which can give non-zero  $A_N$ 's in the framework of quantum chromodynamics (QCD) and quark or quark-parton models. The existing models can approximately be divided into two categories: (1) perturbative QCD based hard scattering models [10-17] and (2) non-perturbative quark-fusion models [19-25].

In the pQCD based hard scattering models [10-17], the cross section for inclusive hadron production in hadron-hadron collision process is expressed as convolution of the following three factors: (a) the momentum distribution functions of the quarks in the colliding hadrons; (b) the cross section for the elementary hard scattering between a constituent (quark, anti-quark or gluon) of one of the colliding hadrons with one of the other; and (c) the fragmentation function of the scattered constituent which describes its hadronization process. The cross section for the elementary hard scattering can be and has been calculated [10] using perturbative QCD. The obtained result [10] shows that, to the leading order, the asymmetry for the elementary process is proportional to  $m_q/\sqrt{s}$  (where  $m_q$  is the quark mass and  $\sqrt{s}$  is the total center of mass energy of the colliding hadron system), which is negligibly small at high energies. In order to describe the observed large asymmetries in terms

of such models, we can make use one or more of the following three possibilities: (i) Look for higher order and/or higher twist effects in the elementary processes which lead to larger asymmetries; (ii) Introduce asymmetric intrinsic transverse momentum distributions for the transversely polarized quarks in a transversely polarized nucleon; (iii) Introduce asymmetric transverse momentum distributions in the fragmentation functions for the transversely polarized quarks, which lead to the observed hadrons. All three possibilities have been discussed in the literature [11-17]. We note that the question whether (or which one of) these possible effects indeed exist(s) is not yet settled. It is clear that under the condition that perturbative QCD is indeed applicable for the description of such processes, it should (at least in principle) be possible to find out how significantly the effects mentioned in (i) contribute to  $A_N$  by performing the necessary calculations. But, in contrast to this, probabilities (ii) and (iii) can only be probed experimentally. This is because the asymmetric momentum distributions mentioned in (ii) and (iii) have to be introduced by hand. Hence, whether such asymmetric distribution functions indeed exist, and how large they are if they exist, are questions which can only be answered by performing suitable experiments.

In the second type of models, the basic elementary processes are quark-antiquark fusions — processes which cannot be calculated by using perturbative QCD. The fusions of the valence quarks of the projectile with suitable antiquarks from the target lead to the mesons observed in the projectile-fragmentation region. Here, the spatial extension of the colliding hadrons and thus hadronic surface effect plays an important role. Together with such surface effect, the orbital motion of the valence quarks in transversely polarized nucleons gives rise to the left-right asymmetries observed in the abovementioned experiments [1-9]. It has been shown [19-25] that such models describe the existing left-right asymmetry data [2-9]. In fact, they not only correctly predicted the change of sign for the asymmetry for  $\pi^+$  and  $\pi^-$  in reactions using polarized anti-proton beam [19-21], the non-existence of the  $x_F$ - $x_T$ -scaling [22], the non-existence of asymmetry in the beam fragmentation region in reaction using  $\pi$ -beam and polarized nucleon target [19-21], but also the left-right asymmetry for  $K^0$  [23]. Furthermore, they also predict the existence of left-right asymmetries for lepton-pair and

for  $K^+$  production [23,25].

Having seen that both types of models can [26] — at least in principle — give non-vanishing values for the left-right asymmetries in high energy single-spin hadron-hadron collisions, we ask: “Can we locate the origin of the observed asymmetries?” “Can we tell which approach is the more appropriate one by comparing such models with the abovementioned data [1-9] ?” The answers to these questions are unfortunately “No!”. The reason is not difficult to find: There are three possibilities, (i), (ii) and (iii), to obtain significant asymmetries in Type One models. What has been measured in such experiments [1-9] is the convolution of all three factors. It is impossible to find out which one is asymmetric by comparing with such measurements. Hence, we are led to the following questions: Is it possible to test the basic assumptions of the models without theoretical preference or prejudice? Is it possible to have experiments with which these basic assumptions can be tested individually ?

In this Letter, we show that these questions can be answered in the affirmative. The experiments we propose are based on the following observations: First, if we can determine the direction of motion of the polarized quark before it fragments into hadrons and measure the left-right asymmetry of the produced hadrons with respect to this direction, we can directly see whether the products of the quark hadronization process is asymmetric with respect to this jet axis. This means such measurements should be able to tell us whether the corresponding quark fragmentation function is asymmetric. Second, there is no hadronization (in other words no fragmentation) of the struck quarks in inclusive lepton-pair or  $W^\pm$ -production processes. Hence, measurements of the left-right asymmetries in such processes should yield useful information on the properties of the factors other than the quark-fragmentation function. Third, while surface effect may play a significant role in hadron-hadron collision processes, it does not exist in deep inelastic lepton-hadron scattering in large  $Q^2$  and large  $x_B$  region where the exchanged virtual photons are considered as “bare photons” [27]. Hence, comparisons between these two kinds of processes can yield useful information on the role played by surface effects. The experiments we propose are

the following.

(A) Perform  $l + p(\uparrow) \rightarrow l + \pi + X$  for large  $x_B$  ( $> 0.1$ , say) and large  $Q^2$  ( $> 10 \text{ GeV}^2$ , say) and measure the left-right asymmetry in the current fragmentation region *with respect to the jet axis*. (See, in this connection, also [14]). Here,  $l$  stands for lepton which can be an  $e^-$  or a  $\mu^-$ ;  $x_B \equiv Q^2/(2P \cdot q)$  is the usual Bjorken- $x$ ,  $Q^2 \equiv -q^2$ , and  $P, k, k', q \equiv k - k'$  are the four momenta of the proton, incoming electron, outgoing electron and the exchanged virtual photon respectively. The  $x_B$  and  $Q^2$  are chosen in the abovementioned kinematic region in order to be sure that the following is true: (1) The exchanged virtual photon can be treated as a bare photon [27]; (2) This bare photon will mainly be absorbed by a valence quark which has large transverse polarization in a transversely polarized proton.

Here, in this reaction, a valence quark is knocked out by the virtual photon  $\gamma^*$  and fragments into the hadrons observed in the current jet. The jet direction is approximately the moving direction of the struck quark before its hadronization; and the struck quark has a given probability to be polarized transversely to this jet axis [28]. The transverse momenta of the produced hadrons with respect to this axis come solely from the fragmentation of the quark. Hence, by measuring this transverse momentum distribution, we can directly find out whether the fragmentation function of this polarized quark is asymmetric.

It should also be mentioned that the struck quark can be a  $u$  or a  $d$  and the relative weight is  $4u(x_B, Q^2) : d(x_B, Q^2)$ , which is enhanced by the corresponding charge factor. Taken together with the fact that  $u$  fragments to  $\pi^+$  or  $\pi^0$  and  $d$  to  $\pi^-$  or  $\pi^0$ , we expect to see the following, if the left-right asymmetry indeed originates from the quark fragmentation. The asymmetries in these processes should be of the same order of magnitude as those observed in hadron-hadron collisions. But  $A_N(\pi^0)$  should be closer to  $A_N(\pi^+)$  than in the hadron-hadron collision processes.

(B) Perform the same kind of experiments as that mentioned in (A) and measure the left-right asymmetry of the produced pions in the current fragmentation region *with respect to the photon direction* in the rest frame of the proton, and examine those events where the lepton plane is perpendicular to the polarization axis of the proton. In such events, the

obtained asymmetry should contain the contributions from the intrinsic transverse motion of quarks in the polarized proton and those from the fragmentation of polarized quarks, provided that they indeed exist. That is, we expect to see significant asymmetries if and only if one of the abovementioned effects is indeed responsible for the asymmetries observed for pion production in single-spin hadron-hadron collisions, and they should be of the same order of magnitude as those observed in hadron-hadron collisions. In contrast, we should see no asymmetry if the observed asymmetries in single-spin hadron-hadron collisions originate from the elementary hard scattering or hadronic surface effects. Note that, compared with experiment (A), this experiment has the advantage that one does not need to determine the jet axis. But it has the disadvantage that one has to fix the lepton-plane and thus reduces the statistics of such measurements.

(C) Perform the same kind of experiments as that in (A), but measure the left-right asymmetry *in the target fragmentation region* with respect to the moving direction of the proton in the collider (e.g. HERA) laboratory frame. By doing so, we are looking at the fragmentation products of “the rest of the proton” complementary to the struck quark (from the proton). Since there is no contribution from the elementary hard scattering processes and there is no hadronic surface effect,  $A_N$  should be zero if the existence of left-right asymmetries is due to such effects. But, if such asymmetries originate from the fragmentation and/or from the intrinsic transverse motion of the quarks in the polarized proton, we should also be able to see them here. To be more precise, for  $\pi^+$  and  $\pi^-$  production,  $A_N$  should be approximately the same as those observed in hadron-hadron collisions. But, for  $\pi^0$ , it should be less than that in the hadron-hadron case. This is because it is more probable for the virtual photon to knock out a  $u$  valence quark from the proton. It should also be mentioned that, compared to the experiment mentioned in (B), this experiment has the following advantages: Here, we do not have the spin transfer factor [14,28] which reduces the polarization, and we do not need to select events according to the lepton planes.

(D) Measure the left-right asymmetry  $A_N$  for  $l\bar{l}$  and/or that for  $W^\pm$  in  $p(\uparrow) + p(0) \rightarrow l\bar{l}$  or  $W^\pm + X$ . Here, if the observed  $A_N$  for hadron production indeed originates from

the quark fragmentation, we should see no left-right asymmetry in such processes. This is because we do not have any contribution from the quark fragmentation here. What we have are contributions from the intrinsic quark distribution functions including orbital motion of valence quarks and/or from those due to surface effect. We therefore expect to see significant asymmetries if these effects indeed exist and are responsible for the asymmetries observed in hadron production processes. The  $Q^2$ -dependence of the asymmetries reflects the  $Q^2$ -dependence of the quark distribution functions or that of the surface effect. (Here,  $Q$  stands for the invariant mass of the lepton pair, or, in the case of  $W$ -production, the mass of  $W$ -boson). It is expected that the surface effect should depend only weakly, if at all, on  $Q^2$ . In the figure, we show the expected  $A_N$  for  $l\bar{l}$  or  $W^\pm$  by assuming that the surface effect does not depend on  $Q^2$ .

Furthermore, it is useful to recall that the leading order elementary processes [29] to lepton-pair production and the first order QCD corrections [30] to them can be easily calculated; and the results are in very good agreement with the cross section data in the unpolarized case, but show zero asymmetry for single-spin hadron-hadron collisions. Hence, if the asymmetry indeed originates from the elementary hard process, it is expected to be very small for lepton-pair production.

In this paper, we have shown that different mechanisms which yield striking left-right asymmetry for inclusive hadron production processes in single-spin hadron-hadron collisions can be differentiated experimentally. Several experiments have been suggested, with which the basic assumptions of such models can be checked individually. The proposed experiments, together with the expected results of different models, are summarized in the table. The outcomes of these experiments are expected to have strong impacts on the study of spin distribution in nucleon and on the study of spin-dependent hadronic interactions, in particular in transversely polarized cases.

This work was supported in part by Deutsche Forschungsgemeinschaft (DFG: Me 470/7-1).

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28. In connection with this experiment, it is useful to recall the following. A transversely

polarized quark in a transversely polarized nucleon remains transversely polarized after it is knocked out of the nucleon by an unpolarized electron (or an unpolarized muon). (See, e.g. [14] and the references given there.) The angle between the polarization direction and the lepton plane looking down stream remains the same before and after the collision. The magnitude of the polarization after the collision is determined by that before the collision times the spin transfer parameter  $D$ , and  $D = (1-y)/(1-y+y^2/2)$ , where  $y \equiv P \cdot q / P \cdot k$ . We see that  $D$  can be quite large for  $y$  not very near to one, which is usually the case in the region of large  $x_B$ .

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## Figure caption

Fig.1 Predictions of the picture proposed in [19] on the left-right asymmetry  $A_N$  for  $p(\uparrow) + p(0) \rightarrow l\bar{l}$  or  $W^\pm + X$  as a function of  $x_F$  at  $\sqrt{s} = 200$  GeV. For lepton pair production, the solid, dashed and dotted lines are for  $Q = 4, 20$  and  $50$  GeV/c<sup>2</sup> respectively.

# TABLES

Table 1. Predictions for left-right asymmetry in the proposed experiments if the asymmetry originates from the different kinds of effects discussed in the text.

process	If the $A_N$ observed in $p(\uparrow) + p(0) \rightarrow \pi + X$ originates from ...			
	quark distribution function	elementary scattering process	quark fragmentation function	orbital motion + surface effect
$l + p(\uparrow) \rightarrow l + \begin{pmatrix} \pi^\pm \\ K^+ \end{pmatrix} + X$	$A_N = 0$	$A_N = 0$	$A_N \neq 0$	$A_N = 0$
in the current fragmentation region	wrt jet axis	wrt jet axis	wrt jet axis	wrt jet axis
for large $Q^2$ and large $x_B$	$A_N \neq 0$	$A_N = 0$	$A_N \neq 0$	$A_N = 0$
	wrt $\gamma^*$ axis	wrt $\gamma^*$ axis	wrt $\gamma^*$ axis	wrt $\gamma^*$ axis
$l + p(\uparrow) \rightarrow l + \begin{pmatrix} \pi^\pm \\ K^+ \end{pmatrix} + X$	$A_N \neq 0$	$A_N = 0$	$A_N \neq 0$	$A_N = 0$
in the target fragmentation region				
for large $Q^2$ and large $x_B$				
$p + p(\uparrow) \rightarrow \begin{pmatrix} l\bar{l} \\ W^\pm \end{pmatrix} + X$	$A_N \neq 0$	$A_N \approx 0$	$A_N = 0$	$A_N \neq 0$
in the fragmentation region of $p(\uparrow)$				

